

PROGRAM TO DEVELOP AN OPTICAL TRANSISTOR AND SWITCH(U)  
WESTINGHOUSE RESEARCH AND DEVELOPMENT CENTER PITTSBURGH  
PA M GARBUNY ET AL. 15 MAR 85 85-9F42-NUTRN-R1

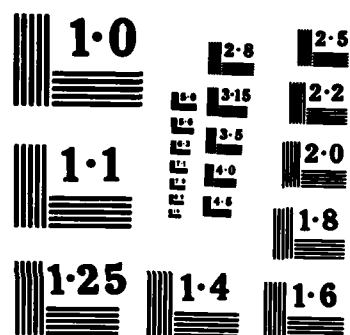
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PROGRAM TO DEVELOP AN OPTICAL TRANSISTOR AND SWITCH

M. Garbuny, T. Henningsen, and R. H. Hopkins

Contract No. F49620-84-C-0103DEF

Air Force Office of Scientific Research  
Bolling AFB  
Washington, DC 20332

March 15, 1985



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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER <b>AFOSR-TR- 85-0487</b>	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PROGRAM TO DEVELOP AN OPTICAL TRANSISTOR AND SWITCH Research Progress & Forecast Report for the period September 1, 1984 to March 30, 1985		5. TYPE OF REPORT & PERIOD COVERED Research Progress & Forecast Report -- 9/1/84 to 3/30/85
7. AUTHOR(s) M. Garbuny, T. Henningsen, and R. H. Hopkins		6. PERFORMING ORG. REPORT NUMBER 85-9F42-NUTRN-R1
9. PERFORMING ORGANIZATION NAME AND ADDRESS Westinghouse R&D Center 1310 Beulah Rd. Pittsburgh, PA 15235		8. CONTRACT OR GRANT NUMBER(s) F49620-84-C-0103DEF
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research /NE Bolling AFB Washington, D.C. 20332		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE March 15, 1985
		13. NUMBER OF PAGES 32
		15. SECURITY CLASS. (of this report) <b>UNCLASSIFIED</b>
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES  (FC)		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) optical. switch. transistors. absorption. relaxation. rate. cross sections. lithium. sodium. transition. line. bands. 47		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Previous work has proposed and analyzed the concept of two light beams inter- acting with a suitable medium to the effect that one beam turns the second beam on or off (an optical switch), or that the modulation in the first beam is ampli- fied in the second (an optical transistor). Switching action was also demon- strated experimentally in uranyl for switching rates up to several kHz. In the present work, a more general survey and analysis was undertaken to identify classes and species of materials for which a particularly effective switching or transistor action can be predicted theoretically. As a class, dense materials,		

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including liquid dyes, have broad absorption band spectra, resulting in low-performance capabilities such as a low transistor gain. In contrast, media in which atomic transitions are free, or shielded, from the fields of other atoms have, as switches and transistors, relatively high speeds of response and low demands on radiation power and mass of interacting materials. As special examples of this class, the performance characteristics of lithium and sodium were calculated and the implications of the results discussed with respect to further action.

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### ABSTRACT

Previous work has proposed and analyzed the concept of two light beams interacting with a suitable medium to the effect that one beam turns the second beam on or off (an optical switch), or that the modulation in the first beam is amplified in the second (an optical transistor). Switching action was also demonstrated experimentally in uranyl for switching rates up to several kHz. In the present work, a more general survey and analysis was undertaken to identify classes and species of materials for which a particularly effective switching or transistor action can be predicted theoretically. As a class, dense materials, including liquid dyes, have broad absorption band spectra, resulting in low-performance capabilities such as a low transistor gain. In contrast, media in which atomic transitions are free, or shielded, from the fields of other atoms have, as switches and transistors, relatively high speeds of response and low demands on radiation power and mass of interacting materials. As special examples of this class, the performance characteristics of lithium and sodium were calculated. These materials allow switching rates or transistor bandwidths of 10 to 20 MHz and require, for a 40  $\mu\text{m}$  diameter fiber, only  $10^{-4}$  to  $10^{-5}$  Torr vapor pressures or, alternatively,  $10^7$  to  $10^8$  atoms deposited on a substrate. Under these conditions, the control power required is 20 to 70  $\mu\text{W}$  for switches and the signal power required is 30  $\mu\text{W}$  to 2 mW for transistor gains ranging from 2.4 to 11.9, respectively. Finally, the report discusses the implications of these results for further action.

## 1. INTRODUCTION

The objective on the first year of this program has been "to develop a mathematical model for the optical transistor and select candidate test materials accordingly." In work done prior to this contract, we found that the uranyl ion in a glass host can be an effective optical switch up to a few kHz, and mathematical modelling showed that it should also have optical transistor characteristics. On this contract, we are now concentrating on finding candidate materials with characteristics more favorable to the demonstration of the optical transistor. We are currently reviewing Condensed Matter (solids and liquids), Molecular Gases, and Free and Quasi-Free Atom Media. While gases and free atoms may seem remote from the requirements of fiber optics and integrated optics waveguides, there are in these groups candidates with interesting parameters, and it may be possible to utilize these characteristics in solid state devices by use of techniques such as ion implantation or surface adhesion. Furthermore, it is possible that the optical transistor effect may be used not only in fiber optic-waveguide type systems, but also for larger volume devices such as optical image amplifiers or switches.

## 2. MATERIAL SELECTION FOR OPTICAL SWITCHES AND TRANSISTORS

The basic concept of optical switches and transistors (OST) is rather simple (see Figure 1). Two beams enter the device.<sup>1</sup> The first, called the control (or pump), acts by inducing absorption on the second, called the signal. As a switch, the control turns the signal on or off (i.e., by reducing it to an acceptable level, such as  $10^{-3}$ , of the initial intensity). In transistor operation, a small variation of the control produces a large variation of the signal, thereby amplifying alternating optical power. Alternatively, the transistor is actually a quantum counter<sup>2</sup> transferring power from one frequency to another more desirable, e.g., for detection. In the basic device, three atomic or molecular levels are involved. The frequency of the control beam is resonant with the transition between levels 1 and 2; hence, the population in level 2 is modulated by the control. The frequency of the signal beam is resonant with the transition between levels 2 and 3; hence the signal is passing or, more or less, absorbed, depending on the population in level 2, i.e., depending on the power of the control beam.

In principle, an almost unlimited number of materials and their spectroscopic energy terms could serve the purposes of OST. However, the number of eligible materials is drastically limited by many practical and inherent conditions. First, the frequencies of control and signal beams may be restricted by the user to certain more or less narrow intervals in the visible and infrared regions or the ultraviolet domain. Second, the OST devices must be designed as components of integrated optical circuitry. This does not imply necessarily that the materials themselves must form fibers or waveguides; they must, however, be compatible with the design requirements of integrated optics, i.e., they must function with rather small active volumes. Third, the materials must operate passively, especially without the aid of remotely

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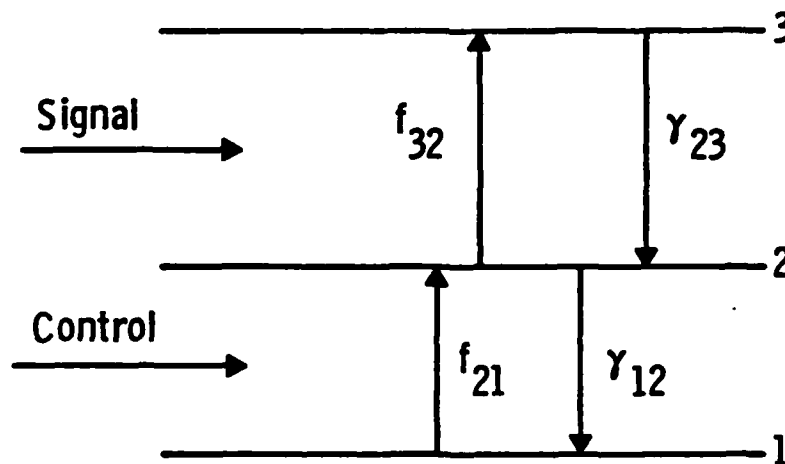


Figure 1. Schematic diagram of optical S&T operation.

delivered electric power. Last but not least, certain stringent inherent conditions must be fulfilled by the energy levels of the material.

Level 2 must have a high relaxation rate,<sup>\*</sup>  $\gamma_{12}$ , to the ground state (level 1), i.e., a short time constant,  $\tau_{12}$ , to accommodate a high switching speed or large transistor bandwidth. On the other hand, the fraction of signal power transmitted is  $\exp(-\sigma_{32}N_2L)$ , where  $\sigma_{32}$  is the absorption cross section for the transition to level 3,  $N_2$  the population density of level 2, and  $L$  the interaction length of the material. Thus, for a given control power,  $N_2$  will be small for short time constants  $\tau_{12}$ . Since  $L$  should also be small, sufficient leverage for the control of the signal beam can only be obtained if  $\sigma_{32}$  is large. This represents a second condition for level 2. However, in the special case of an optical switch for which relatively long periods of bistable operation are desired, the conditions for level 2 can be considerably relaxed. A long lifetime of level 2 is in fact an advantage in this special case since it reduces the required control power.

Level 3 should have a relaxation rate  $\gamma_{23} > \gamma_{12}$  so that an atom or molecule in level 2 can make many absorbing transitions to level 3 before it falls back to the ground state. A subsidiary condition for level 3 is that it have only negligible probability of relaxing into a state other than level 2 and, in particular, that  $\gamma_{13} = 0$ .

How do various materials fulfill the requirements stated in the foregoing? This question is of crucial importance for the further planning and procedure of this work. In the following, conclusions are summarized for the main classes of materials.

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<sup>\*</sup>In this report we follow the convention of designating in  $\gamma_{12}$ ,  $\sigma_{32}$ , etc., the first subindex as the final level, the second subindex as the initial level, of a transition.

## 2.1 Condensed Matter (Solids and Liquids)

Solids, particularly if they can be constructed as fibers or waveguides, have the a-priori advantage that they lend themselves easily to use as integrated optics components. Liquids, such as dyes, share this advantage to some extent since they can be suspended in capillary fibers. Certain organic crystals and fibers also belong to the category of dense materials.

The dense matter state is characterized by the strong coupling that, in general, exists between the radiating or absorbing electric dipoles. This strong coupling entails broad bands (rather than lines) in the spectra with resulting low-absorption cross sections and radiative decay rates. Broad absorption bands have the advantage that they do not require highly frequency-selective power sources for excitation, but the disadvantage that such bands may overlap for control and signal levels. Initial analysis and experiments for the demonstration of the OST concept<sup>1</sup> were carried out on the example of  $\text{UO}_2^{2+}$  (uranyl). This solid has the following pertinent parameters<sup>2,3</sup>:

$$\begin{array}{ll} \sigma_{21}(460 \text{ nm}) = 1 \cdot 10^{-20} \text{ cm}^2 & \gamma_{12} = 0.00478 \cdot 10^6 \text{ sec}^{-1} \\ \sigma_{32}(460 \text{ nm}) = 0.36 \cdot 10^{-17} \text{ cm}^2 & \gamma_{23} = 2.5 \cdot 10^6 \text{ sec}^{-1} \text{ (radiationless)} \\ \sigma_{32}(570 \text{ nm}) = 1.39 \cdot 10^{-17} \text{ cm}^2 & \gamma_{13} = 0.6 \cdot 10^6 \text{ sec}^{-1} \end{array}$$

The experiments demonstrated optical switching action with a response time  $\tau_{12}$  of about 200  $\mu\text{sec}$  ( $= \gamma_{12}^{-1}$ ), so that a switching rate up to a few kHz is possible. In dense materials excited states can relax by the relatively fast and radiationless energy transfer to phonons as seen for the rate  $\gamma_{23}$  in uranyl. This process here has the advantage of avoiding reradiation by spontaneous emission of the absorbed signal photons. Such reradiation has the effect of somewhat reducing the "net" absorption cross section  $\sigma_{32}$  at the signal frequency.

## 2.2 Molecular Gases

A systematic study of candidate materials for OST operation has to include molecular gases because of the vast number of possible energy term schemes and transitions. Nevertheless, the application of molecular transitions to OST devices encounters several problems.

Electronic transitions in molecules are fast, but lie, for most gases, in a part of the ultraviolet region which is not likely to be of interest in OST applications or even compatible with integrated optics.

Vibrational transitions extend from wavelengths in the far infrared to wavelengths as short as  $1.5 \mu\text{m}$  (if the first vibrational overtones are included). The near infrared region as such is not excluded from considerations since sources of sufficient power and detectors of sufficient sensitivity are available in this domain. Instead, the main problem lies in the long radiative lifetimes of excited vibrational levels, typically in the range of 10-50 msec. Collisional deexcitation to lower levels at suitable densities can increase the relaxation rates by orders of magnitude in a radiationless process not unlike the phonon transfer in solids. However, vibrational energy transfer by collisions affects all vibrational levels, although not with the same cross sections. Whether this fact can be utilized to fulfill the level requirements stated before is a complex question.

## 2.3 Free and Quasi-Free Atom Media

A third class of candidate materials is the state of free atoms, such as monatomic gases or the vapors of mercury and the alkali metals at low pressures. In these media, the electronic energy states of the atoms are, ideally, unperturbed by the fields of neighboring or colliding atoms. As a result, spontaneous emission and absorption lines have very narrow spectral widths, viz., in terms of the line frequency  $\nu$ , typically a halfwidth  $\Delta\nu_h^D \approx 10^{-6} \nu$  for Doppler broadening, and if the latter can be avoided, the natural width  $\Delta\nu_h^N \sim 10^{-8} \nu$ .

The free-atom state can be approximated by atoms that are weakly bound on substrates such as on the surface of a fiber (similar to the method of internal reflection spectroscopy) or the inside wall of a hollow fiber. Another approximation to the free-atom state are interstitial atoms or ions with unfilled d- or f-shells (such as the rare earths) in transparent host solids. Electronic transition within these shells is shielded from the fields of the surrounding host material environment and therefore yields sharp lines. Such media are called here "quasi-free atoms." Their line spectra are not as sharp as those of free atoms, but orders of magnitude narrower than those of the bands normally in solids.

In the following we use certain relationships of radiation theory for a comparison between free atoms and the other media in terms of the constants important for OST operation. These relationships have been used in the computation of the performance characteristics expected from the examples in Section 3.

### 2.3.1 Computation of Absorption Cross Sections and Radiative Decay Rates

Assume a medium with an absorption coefficient  $k_\nu$  at the frequency  $\nu$ . A beam of initial intensity  $I_{\nu 0}$  will then be attenuated to  $I_\nu$  after passing through a length  $L$  of the medium:

$$I_\nu = I_{\nu 0} e^{-k_\nu L} \quad (1)$$

For small values of the exponent, to which the case of the optical transistor can be reduced, Equation 1 becomes linear so that one obtains for the fraction of power absorbed from the initial power  $P_{\nu 0}$

$$P_\nu^A / P_{\nu 0} = (1 - I_\nu / I_{\nu 0}) \approx k_\nu L; \quad k_\nu L \ll 1 \quad (2)$$

The coefficient  $k_\nu$  is a function of the frequency  $\nu$ , described by the absorption line profile. The line may be narrow or broadened to a band. However, radiation theory makes a very general statement about the area under the profile, viz.,



$$\int k_{\nu} d\nu = \frac{\pi e^2}{mc} N f_{mn} = 0.0265 f_{mn} N \quad (3)$$

where  $e$  and  $m$  are charge and mass of the electron,  $c$  the speed of light in vacuo,  $N$  the number density of atoms [ $\text{cm}^{-3}$ ], and  $f_{mn}$  the oscillator strength<sup>\*</sup> of the transition to a level  $m$  from a level  $n$  (see Figure 2). The numerical value in Equation 3 is computed for CGS units of all variables. It is seen that the absorption (coefficient) integral is independent of linewidth and frequency.

To evaluate the absorption cross section from Equation 3, we transform the area under the absorption line profile into a rectangle of the line peak  $k_{\text{max}}$  as height and a linewidth  $\Delta\nu$  as base so that

$$\int k_{\nu} d\nu = k_{\text{max}} \Delta\nu \quad (4)$$

The cross section  $\sigma$  is then given by the relationship between absorption coefficient and absorber density, viz.,

$$k_{\text{max}} = N\sigma \quad (5)$$

The absorption cross section follows thus from the last three equations as

$$\sigma = 0.0265 f_{mn} / \Delta\nu \quad (6)$$

The linewidth  $\Delta\nu$  defined by Equation 4 will be of the same order of magnitude as the FWHM width, which is dependent on the line shape (e.g., Gaussian or Lorentzian).

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<sup>\*</sup>The oscillator strength derives from the classical model of an electron oscillating around a positive charge for which the absorption integral in Equation 3 becomes simply  $\pi e^2/mc$ . In the actual quantized level structure of atoms,  $f_{mn}$  represents the factor by which any particular transition from  $n$  to  $m$  differs in strength from the classical model.

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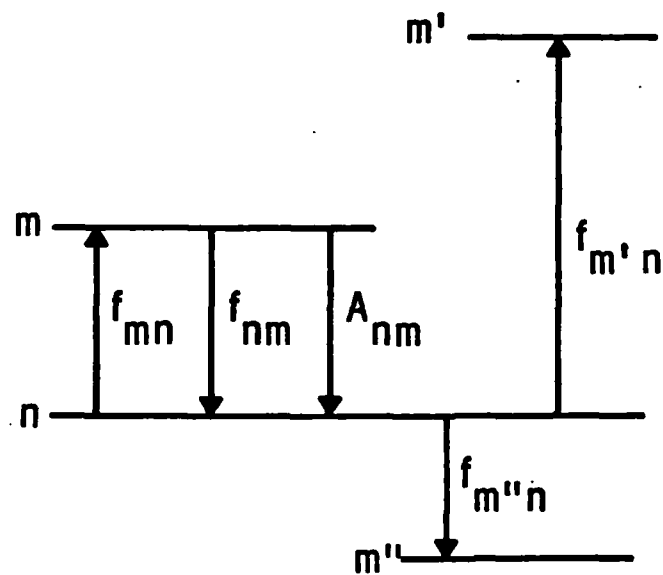


Figure 2. Designation of transition parameters.

Assuming an  $f$ -value of 0.1 and a linewidth  $\Delta\nu = 1.10^9 \text{ sec}^{-1}$ , one obtains from Equation 6 an absorption cross section  $\sigma = 3.10^{-12} \text{ cm}^2$ . Such cross sections can be a factor of  $10^6$ , or more, larger than those of the absorption bands in solids. Thus, in an OST device the population excited into level 2 by the control beam can be  $10^6$  times smaller to achieve the same absorption as in a solid under otherwise equal conditions.

Of equal importance is the radiative decay rate (the Einstein spontaneous emission probability)  $A_{nm}$  ( $= \gamma_{nm}$ ) from a level  $m$  to  $n$  (see Figure 2). From radiation theory,

$$A_{nm} = 8\pi^2 \frac{e^2}{mc^3} \nu^2 f_{nm} = 7.34 \cdot 10^{-22} \nu^2 f_{nm} \quad (7)$$

where  $f_{nm}$  is the oscillator strength of stimulated emission from (a higher) level  $m$  to a (lower) level  $n$ . Equation 7 has been derived for electronic dipole transitions in free atoms. It is not valid for radiationless decay or for other conditions governing the solid state.

Assuming a frequency  $\nu = 4.10^{14} \text{ sec}^{-1}$  (corresponding to a wavelength of 740 nm) and again  $f_{nm} = 0.1$ , one obtains  $A_{nm} = 1.2.10^7 \text{ sec}^{-1}$ . Thus, the speed of response in OST devices can be relatively high. Furthermore, the  $f$ -values chosen in the two previous examples are quite conservative and can usually be up to an order of magnitude larger for transitions between the first few levels above the ground state.

The  $f$ -values are implicit in measurements of either emission or absorption. The following relationship between the  $f$ -values for absorption and emission applies:

$$f_{nm} = - \frac{g_n}{g_m} f_{mn} \quad (8)$$

where the  $g_n$  and  $g_m$  are the statistical weights of states  $n$  and  $m$ , respectively. The negative sign in Equation 8 results from the fact that the two  $f$ -values refer to energetically opposite effects, viz., one

to absorption, the other to spontaneous emission. Equations 7 and 8 can be used to determine  $A_{nm}$ ,  $f_{nm}$ , and  $f_{mn}$  from a measurement of either spontaneous emission intensity or absorption between levels  $n$  and  $m$ . This is important since published data are almost always based on only one type of measurement, usually emission.

Certain other considerations apply to the selection of suitable levels for optical transistor operation. It is seen from Equations 7 and 8 that, except for the  $g$ -values, the three constants  $A_{nm}$ ,  $f_{nm}$ , and  $f_{mn}$  are proportional to each other. This proportionality, of course, does not extend to relationships between different transitions, such as between  $A_{nm}$  and  $f_{m'n}$  or  $f_{m''n}$  (see Figure 2). Aside from different frequencies  $\nu$ ,  $f_{mn}$ ,  $f_{m'n}$ , and  $f_{m''n}$  will be quite different. There exists, however, a condition of restraint in the  $f$ -sum rule:

$$\sum_m f_{mn} = z \quad (9)$$

where  $z$  is the number of electrons in the state  $n$  (usually equal to 1). As shown in Figure 2, this sum contains positive and negative values  $f_{mn}$ , corresponding to absorption and (stimulated) emission so that with Equation 8, one can also write for Equation 9

$$\sum_m f_{mn} - \sum_m \frac{g_m}{g_n} f_{nm} = z \quad (10)$$

where the first term on the left refers to absorption, the second to emission. The sums extend over all transitions from the level  $n$  which are permitted by the selection rules, although in emission the lower levels  $m$  may be in filled shells. The balance of  $f$ -values in Equation 10 makes it possible for OST operation to select a level 3 (see Figure 1) for which  $f_{23}$ , hence  $A_{23}$ , is appreciably larger than  $f_{12}$ , hence  $A_{12}$ . In this case, therefore, the radiative decay rates of levels 2 and 3 may fulfill the transistor condition stated at the start of this section.

In summary, we conclude that free atoms and, to some extent, quasi-free atoms offer absorption cross sections and radiative decay rates which are several orders of magnitude larger than those of other materials. As a result, fast response is possible coupled with minimal demand on the mass of active material and optical power. The analysis also predicts conditions for optical transistor gain; to this has to be added that parasitic (by-pass) transitions (such as those which give rise to  $a_{31}$  in the previous analysis<sup>1</sup>) can be easily avoided. Such media therefore deserve the first priority of theoretical and experimental investigation for OST devices.

### 3. PERFORMANCE EXPECTATIONS FOR OST DEVICES USING ALKALI METAL ATOMS

According to the preceding section, the materials of apparently greatest promise for OST operation are the media which consist of free atoms or, at least, contain quasi-free atoms. However, the choice must be limited to those elements (or their ions) for which the transition  $\nu_{21}$  in the three-level system (level 1 always the atomic ground state) lies in a wavelength range compatible with restrictions of integrated optics. A survey of atomic line spectra reveals that there are two groups of media with elements fulfilling the wavelength condition. These are the metals in the first column of the periodic system, particularly the alkali atoms, and, second, transparent crystals or glasses which contain atoms or ions with unfilled shells such as the rare earths. The atoms of such media as the rare gases require excitation to level 2 in the far ultraviolet region, which is at present impossible, or at least extremely difficult, to match with the technology of integrated optics.

We have chosen to first investigate the performance of the alkali metals for several reasons. Spectroscopic  $f$ - and  $A$ -data are to a large extent available from tables,<sup>5</sup> although one has to derive, e.g.,  $f_{mn}$ , from the experimentally determined  $f_{nm}$  with Equation 8. Thus, theoretical performance predictions for OST devices are possible with good accuracy. Subsequent verification by experiments with the vapor of alkali metals is not too difficult. Last but not least, the free-atom state may be approximated with quasi-free atom embodiments for practical devices.

The transition  $\nu_{12}$  lies in the visible range for all alkali metals. The transitions to a level 3 have the feature that relaxation by radiation from level 3 to level 1 is forbidden by selection rules, i.e.,

$$\gamma_{13} = 0 \quad (11)$$

Thus the coefficient  $a_{31}$ , which in the previous analysis<sup>1</sup> played an important complicating role, vanishes for these atoms:

$$a_{31} = \gamma_{13}/(\gamma_{13} + \gamma_{23}) = 0 \quad (12)$$

This fact simplifies all relationships starting with rate equations. We have thus for the absorbed pump power required to maintain an excited population density  $N_2$  in level 2:

$$P_{abs} = n_2 \gamma_{12} h\nu_{12} = LaN_2 \gamma_{12} h\nu_{12} \quad (13)$$

where  $n_2$  is the total population in level 2 contained in a volume of length  $L$  and cross-sectional area  $a$ . The application of Equation 13 to OST performance evaluation differs for switches and transistors.

### 3.1 Optical Switch

Here the objective is the bistable operation of signal power  $S$  between full transmission of a signal  $S$  and its attenuation by large factor, e.g., 30 db ( $10^3$ ) to  $S_f$ :

$$S_f = S_o e^{-N_2 \sigma_{32}^{eff} L} \quad (14)$$

where the "effective absorption coefficient"  $\sigma_{32}^{eff}$  includes such effects as stimulated emission. The objective includes a low level of the required absorbed pump power and options of switching rates from zero to the highest possible value. Introduction of Equation 14 into Equation 13 yields for the necessary absorbed power:

$$P_{abs} = a \frac{\gamma_{12} h\nu_{12}}{\sigma_{32}^{eff}} \ln (S_o/S_f) \quad (15)$$

It is seen that the switching rate is limited by the radiative decay rate  $\gamma_{12}$  and the minimum power by that rate and the cross section  $\sigma_{32}$ .

### 3.2 Optical Transistor

Here we are concerned with changes of signal power  $S_f$  produced by a small change of the control power  $P_o$  around an operating point given by

$$P_{abs} = P_o (1 - e^{-N_1 \sigma_{21} L}) \quad (16)$$

and

$$S_f = S_o e^{-N_2 \sigma_{32} L} \quad (17)$$

A small variation of the control power  $P_o$  then produces, in first order, a linear change  $\Delta P_{abs}$ . This produces a change  $\Delta S_f$  in signal transmission of opposite sign.

The objective of the transistor is to maximize the gain  $G$  defined by

$$G = \left| \frac{\Delta S_f}{\Delta P_o} \right| \quad (18)$$

Here, with Equation 16

$$\frac{\Delta S_f}{\Delta P_o} = - \frac{\Delta S_{abs}}{\Delta P_{abs}} (1 - e^{-N_1 \sigma_{21} L}) \quad (19)$$

The mechanism of gain by "recirculation" of quanta has already been described for uranyl,<sup>1</sup> for radiationless decay from level 3 to level 2. We describe the process again for alkali metal spectra.

Each alkali atom which has been excited by the quantum  $h\nu_{21}$  dwells in level 2 for a lifetime  $\gamma_{12}^{-1}$ . During this lifetime a number of quanta  $h\nu_{32}$  may be absorbed by the atom from the signal power to



level 3, which reradiates them at the rate  $\gamma_{23}$  spontaneously in random directions. Thus, there results for the absorption ratio:

$$\frac{\Delta S_{\text{abs}}}{\Delta P_{\text{abs}}} = \frac{\gamma_{23} \nu_{32}}{\gamma_{12} \nu_{21}} \quad (20)$$

Thus, one obtains with Equations 18 and 19 the gain

$$G = \frac{\gamma_{23} \nu_{32}}{\gamma_{12} \nu_{21}} (1 - e^{-N_1 \sigma_{21} L}) \quad (21)$$

The depletion of the control beam can be complete, i.e., the factor in Equation 21 contained in the bracket can approach unity, without bringing other limitations into play so that the gain approaches that given by Equation 20. This result obtained by partly intuitive reasoning is valid only for the special case that the statistical weights of levels 2 and 3 are equal. A more rigorous (see Appendix 1) treatment based on the rate equations yields for the buildup of the gain with increasing signal power  $S_o$ :

$$G = G_f \times G_{ph} = \left( \frac{\nu_{23}}{\nu_{12}} \right) \times \frac{\gamma_{23} g_3}{\gamma_{12} g_2} \frac{1}{1 + \frac{1}{\sigma_{23} \frac{g_2}{g_3} \frac{1}{\gamma_{23}} \frac{S_o}{ah \nu_{23}}}} \quad (22)$$

Equation 22 can be written in the form

$$G = G_{\text{sat}} \left( \frac{1}{1 + S_h/S_o} \right) \quad (23)$$

where the saturation gain

$$G_{\text{sat}} = \left( \frac{\nu_{23}}{\nu_{12}} \right) \times \left( \frac{\gamma_{23} g_3}{\gamma_{12} g_2} \right)$$

is the maximum gain that can be obtained in a particular material.

$$S_h = ah \nu_{23} \left( \frac{g_3}{g_2} \right) \frac{\gamma_{23}}{\gamma_{32}}$$

is the "half max gain" signal power, i.e., the signal power required to obtain half of the theoretical max gain,  $G_{\max}$ , in the device. The smaller this number is, the less signal power is required to operate the device.

Figure 3 shows the normalized gain,  $\frac{G(S_o)}{G_{(\max)}}$  as a function of the signal power,  $S_o$ , which is normalized to the "half max gain" signal power  $S_h$ .

The numerical evaluations of the parameters important for OST, notably Equations 15 and 21, require a knowledge of the absorption cross sections and transition probabilities. These are directly available, or can be computed, from Tables published by the National Bureau of Standards.<sup>5</sup> The data are based on the intensities of the emission lines of 70 elements, limited, however, to the wavelength range from 200 to 900 nm. This material has been largely, although not completely, sufficient for the evaluation of the alkali metals. Necessary recalculations of these data were performed by using the relationships given in Section 2.

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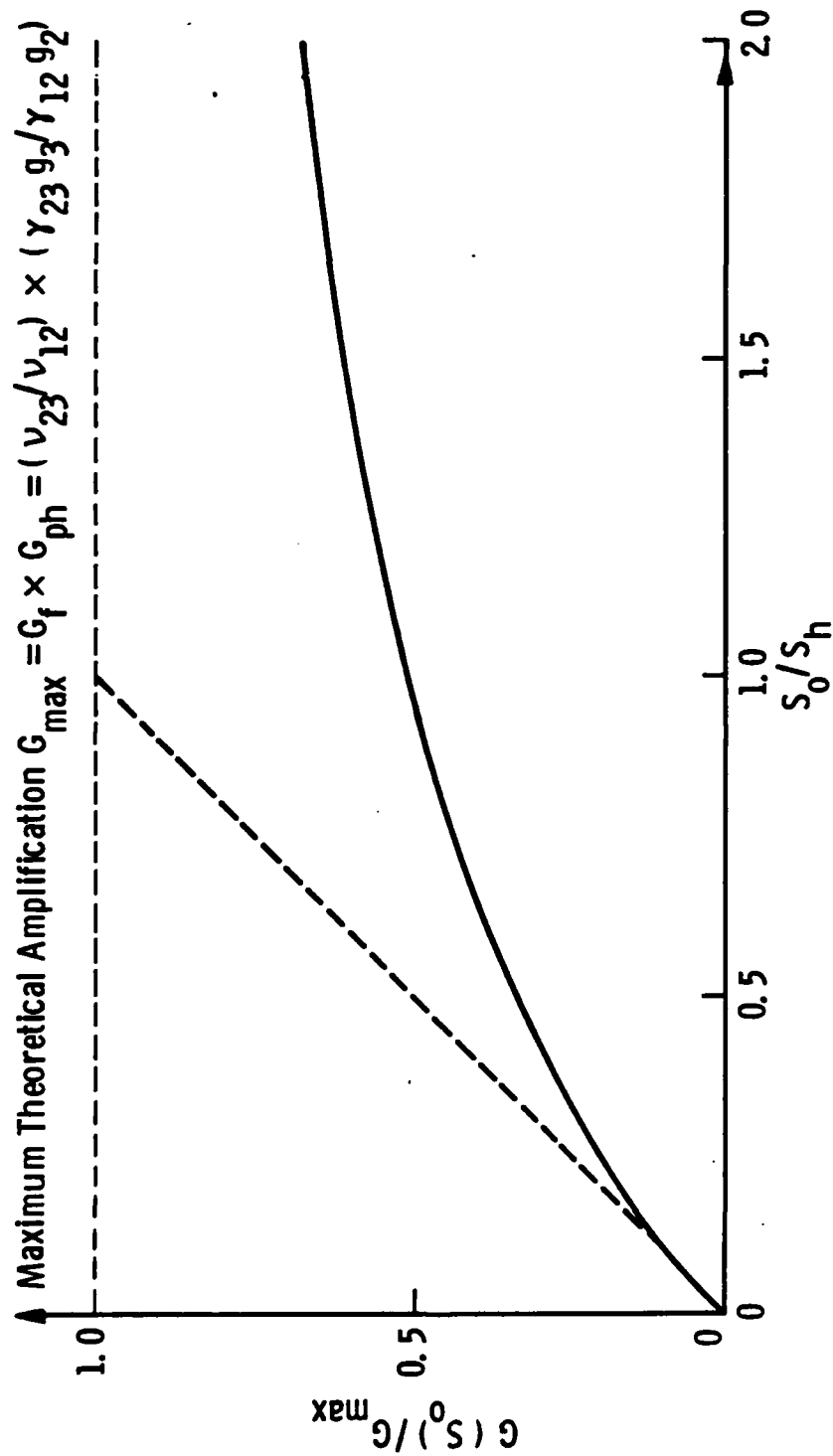


Figure 3. Normalized gain as a function of normalized signal power for a transistor.

#### 4. EXAMPLES

A choice of suitable atomic transitions is governed by the following principles:

- (1) Level 1 is the ground state.
- (2) For the switching device, according to Equation 15,  $\gamma_{12}v_{12}/\sigma_{32}$  should be a minimum to keep the power demand for operation as small as possible. However,  $\gamma_{12} = A_{12}$  should be large enough to fulfill the speed of response requirement. Hence,  $\sigma_{32}$  should be as large as possible.
- (3) For the optical transistor, according to Equation 22,  $(\gamma_{23}g_3v_{23}/\gamma_{12}g_2v_{12})$ , which is the saturation gain of the device, should be as large as possible. The other parameters in Equation 22 determine how large the signal power  $S_0$  must be to reach the saturation gain within a few percent. In addition, the radiative decay rates should be large enough to meet the bandwidth requirements for the transistor.

The NBS tables<sup>5</sup> yield, for every measured emission line intensity, the values  $g_n A_{nm}$  and  $g_n f_{nm}$  ( $m > n$  represents the upper level). The Einstein  $A_{nm}$  is here always equal to  $\gamma_{nm}$ . In lines with resolved fine structure, the statistical weight of a level equals  $(2j+1)$ . Where the tables report unresolved fine structure lines, the  $g$ -values correspond to the sum of the individual fine structure level  $g$ -values. The absorption oscillator strength  $f_{mn}$  follows from  $f_{nm}$  via Equation 8. Equation 6 yields then the absorption cross section  $\sigma_{mn}$ . We adopted a model of alkali metal vapor at densities corresponding to pressures of  $10^{-3}$  to  $10^{-5}$  Torr. At such densities, the FWHM linewidth in  $\text{sec}^{-1}$  is given by the Doppler width

$$\Delta v_h = 7.17 \cdot 10^7 \nu (T/M')^{1/2} \quad (24)$$

where T represents the temperature (K) and M' the molecular weight of the material.

#### 4.1 Lithium

Figure 4 shows a diagram of energy term levels and transitions of lithium. As the first element of the second shell (ground state  $1s^2 2s^2 S_{1/2}$ ), lithium has the feature that the lowest D-level is 3D (because of the quantum condition  $l \leq n-1$ ). This has the consequence that the transition  $2P \rightarrow 3D$  has several advantages for OST not present among the other alkali metals. The transitions selected for levels 1  $\rightarrow$  2 and levels 2  $\rightarrow$  3, respectively, are shown in bold arrows in Figure 4. The following are the data for the transitions and their levels.

<u>Level 1</u>	<u>Level 2</u>	<u>Level 2</u>	<u>Level 3</u>
$2s^2 S_{1/2} \rightarrow 2p^2 P_{1/2,3/2}$		$2p^2 P_{1/2,3/2} \rightarrow 3d^2 D_{3/2,5/2}$	
$\lambda_{12} = 670.78 \text{ nm}$		$\lambda_{23} = 610.36 \text{ nm}$	
$\nu_{12} = 4.47 \cdot 10^{14} \text{ sec}^{-1}$		$\nu_{23} = 4.91 \cdot 10^{14} \text{ sec}^{-1}$	
$g_2 = 6, g_1 = 2$		$g_3 = 10, g_2 = 6$	
$g_2 A_{12} = 1.2 \cdot 10^8 \text{ sec}^{-1}$		$g_3 A_{23} = 13 \cdot 10^8 \text{ sec}^{-1}$	
$g_2 f_{12} = 0.8$		$g_3 f_{23} = 7.5$	
$\gamma_{12} = A_{12} = 0.2 \cdot 10^8 \text{ sec}^{-1}$		$\gamma_{23} = A_{23} = 1.3 \cdot 10^8 \text{ sec}^{-1}$	
$f_{21} = 0.4$		$f_{32} = 1.25$	
$\Delta v_h = 4.14 \cdot 10^9 \text{ sec}^{-1}$		$\Delta v_h = 4.55 \cdot 10^9 \text{ sec}^{-1} (T = 500 \text{ K})$	
$\sigma_{21} = 2.85 \cdot 10^{-12} \text{ cm}^2$		$\sigma_{32} = 8.11 \cdot 10^{-12} \text{ cm}^2$	

The transition shown in Figure 4 of  $3d^2 D_{3/2,5/2} \rightarrow 3p^2 P_{1/2,3/2}$  (in the far infrared) is expected to be quite weak and has been ignored.

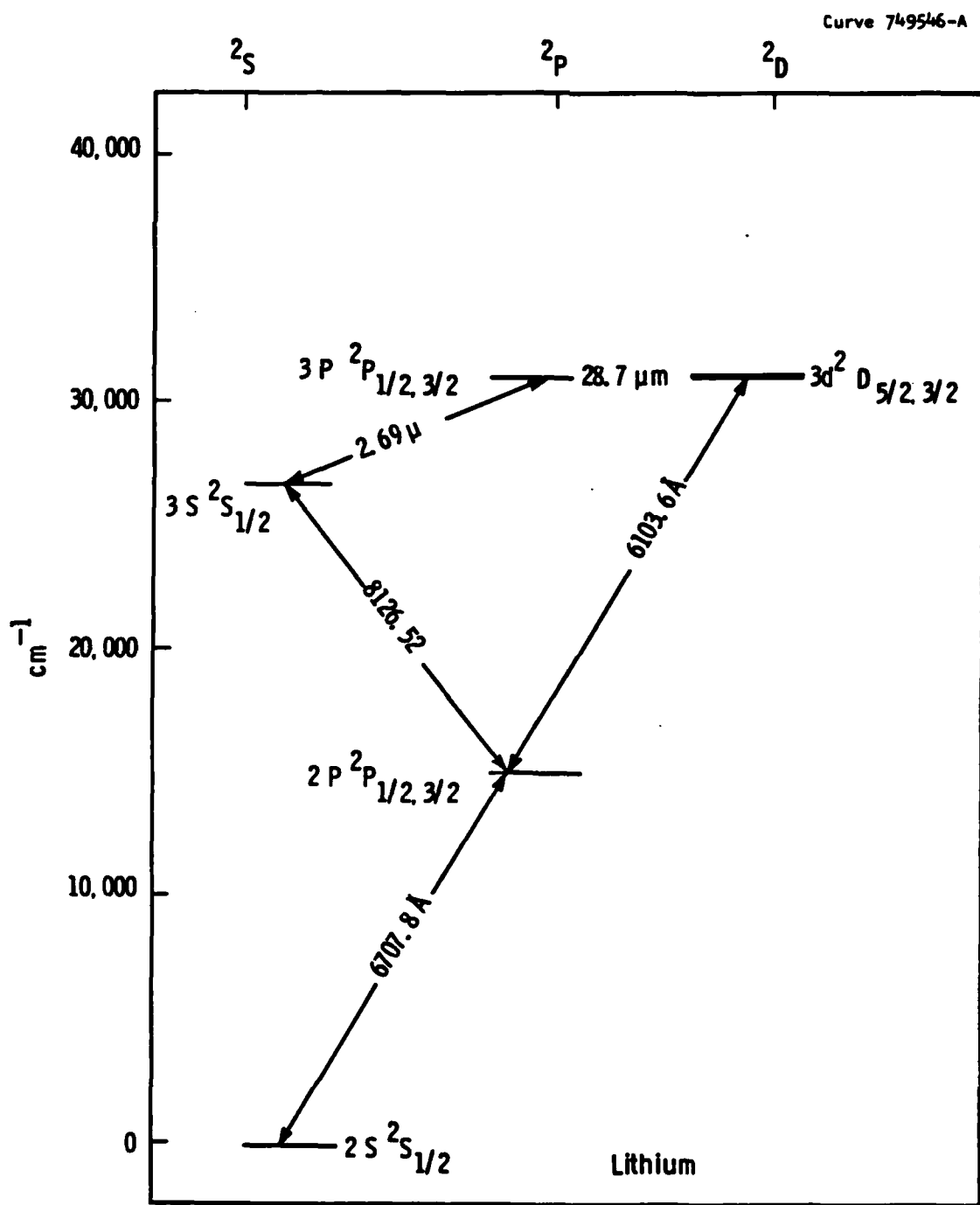


Figure 4. Lithium-spectrum: heavy lines are selected transitions.

#### 4.1.1 Optical Switch

Using Equation 15 with  $h = 6.63 \cdot 10^{-34}$  (Jsec), we have for the required control power density:

$$P_{\text{abs}}/a = 5.0 \text{ W/cm}^2 \quad (25)$$

or for the power  $P_0$  required for the cross-sectional area  $a$  of a 40  $\mu\text{m}$  diameter fiber,

$$P_0 = 64 \text{ } \mu\text{W} \quad (26)$$

This is the control power required to attenuate the signal power  $S_0$  to  $S_f = 10^{-3}S_0$  (30 dB attenuation). The molecular density  $N_2$ , and the gas density  $N$  to be initially provided, follow from Equation 14:

$$N_2 \sigma_{32}^{\text{eff}} L = \ln (S_0/S_f) = 6.9 \quad (27)$$

This yields for  $N_2L$ :

$$N_2L = 8.5 \cdot 10^{11} \text{ cm}^{-2} \quad (28)$$

Allowing for the effect of stimulated emission from level 2 to level 1, we find that a gas density of

$$NL = 2.5 \cdot 10^{12} \text{ cm}^{-2} \quad (29)$$

is sufficient for steady-state conditions. Equation 29 corresponds to a pressure of  $10^{-4}$  Torr for  $L = 1$  cm length. The significance of Equation 29 is that, as shown by experimental and theoretical work,<sup>6</sup> metal atoms in the vapor phase at low pressures may fail to condense on selected substrates at normal temperatures. This is the case, even if the vapor pressure of the metal in bulk is much lower at that temperature than that of the metal atoms in the vapor phase.

The switching speed is determined by the slowest decay rate, viz.,  $A_{12} = 0.2 \cdot 10^8 \text{sec}^{-1}$ . The switching rate is therefore limited to 10 MHz, about  $10^3$  times faster than uranyl.

#### 4.1.2 Optical Transistor

According to Equation 23, the gain can be written in the form

$$G = G_{\text{sat}} \left( \frac{1}{1 + S_h/S_0} \right) \quad (30)$$

With the data for lithium, the saturation gain  $G_{\text{sat}}$  equals

$$G_{\text{sat}} = (\gamma_{23}g_3/\gamma_{12}g_2) \cdot (\nu_{23}/\nu_{12}) = 10.8 \cdot 1.1 = 11.9 \quad (31)$$

where we have separated the (saturation) photon multiplication and the photon energy gain factors, respectively. The signal power  $S_h$  (see Equation 23) required to reach  $G_{\text{sat}}/2$  equals in flux density

$$S_h/a = 8.7 \text{ W/cm}^2 \quad (32)$$

so that for a 40  $\mu\text{m}$  fiber

$$S_h = 110 \text{ } \mu\text{W} \quad (33)$$

The variation of the gain with  $S_0$  is thus

$$G = 11.9 \left( \frac{1}{1 + 110/S_0} \right) \quad (34)$$

with  $S_0$  in  $\mu\text{W}$ . For  $S_0 = 2200 \text{ } \mu\text{W}$ ,  $G$  reaches saturation within about 5%. Equation 34 is plotted in Figure 5.

#### 4.2 Sodium

A procedure similar to that for lithium was adopted for sodium. In particular, analogous transitions between the levels were selected



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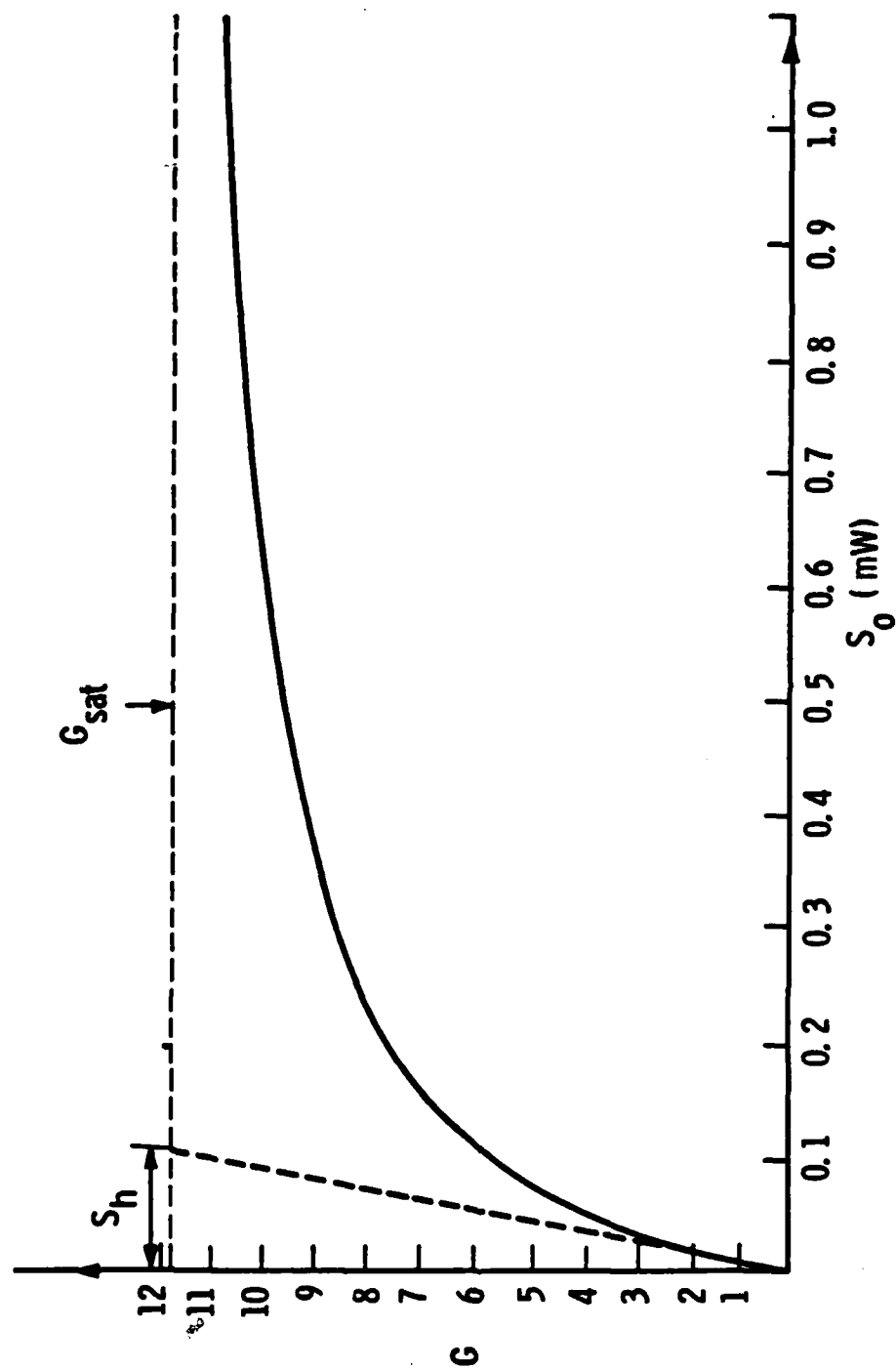


Figure 5. Gain in a lithium transistor.

(see Figure 6). In sodium, the fine structure of level 2 is a doublet of sufficient spacing so that the NBS tables cite separately the transitions to and from the two sublevels, viz.,  $3p\ ^2P_{1/2}$  and  $3p\ ^2P_{3/2}$ . Nevertheless, the parameters important for OST operation are essentially the same numerically for both sublevels. A small advantage lies in the choice of the  $^2P_{1/2}$  sublevel because of a slightly preferable frequency ratio and because (in the presence of stimulated emission from level 2 to level 1) its statistical weight,  $g=2$ , requires fewer sodium atoms than the sublevel with  $g=4$ . The important data of the selected transition are the following:

$3s\ ^2S_{1/2} \rightarrow 3p\ ^2P_{1/2}$	$3p\ ^2P_{1/2} \rightarrow 3d\ ^2D_{3/2,5/2}$
$\lambda_{12} = 589.592\text{ nm}$	$\lambda_{23} = 818.327\text{ nm}$
$\nu_{12} = 5.08 \cdot 10^{14}\text{ sec}^{-1}$	$\nu_{23} = 3.67 \cdot 10^{14}\text{ sec}^{-1}$
$A_{12} = 0.45 \cdot 10^8\text{ sec}^{-1}$	$A_{23} = 0.44 \cdot 10^8\text{ sec}^{-1}$
$g_2 = g_3 = 2$	$g_3 = 10, g_2 = 2$
	$\sigma_{32} = 5.30 \cdot 10^{-11}\text{ cm}^2\ (T=500\text{ K})$

#### 4.2.1 Optical Switch

With calculations as in Section 4.1.1, one finds for 30 db attenuation

$$P_{\text{abs}}/a = 2.0\text{ W/cm}^2 \quad (35)$$

Control power in a 40  $\mu\text{m}$  diameter fiber:

$$P_0 = 25\ \mu\text{W} \quad (36)$$

Number of Na atoms required:

$$NL = 7 \cdot 10^{11}\text{ cm}^{-2} \quad (37)$$

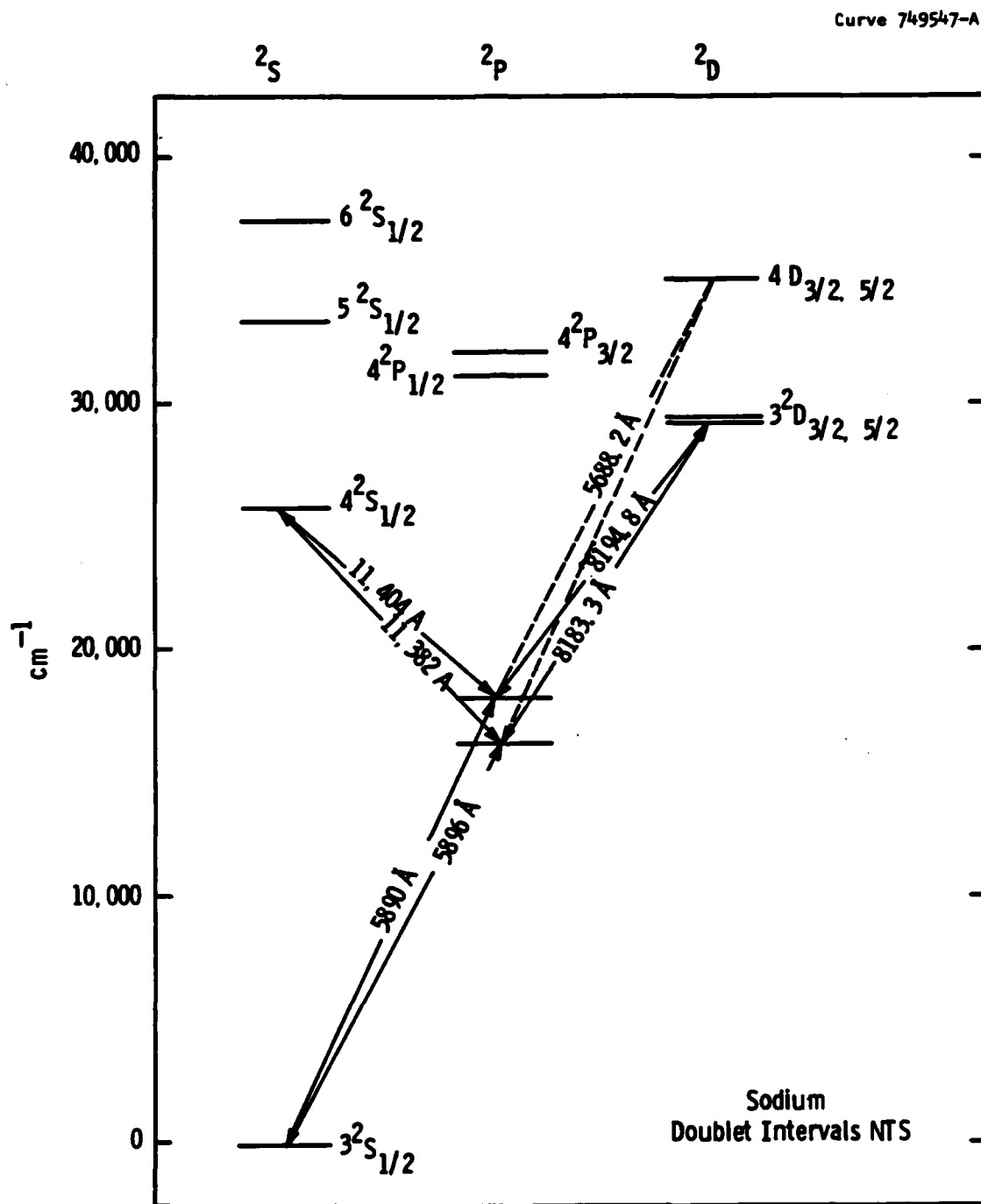


Figure 6. Sodium spectrum: heavy lines are selected transitions.

Limit of switching speed:

$$A_{23} = 0.44 \cdot 10^8 \text{sec}^{-1} \quad (38)$$

Comparison with Equations 25 to 29 shows that sodium performs somewhat better as a switch than lithium. It requires less cut-off power, less material, and allows a switching rate of about 20 MHz.

#### 4.2.2 Optical Transistor

The saturation gain, written as the product, respectively, of photon amplification and energy gain, is

$$G_{\text{sat}} = 4.89 \cdot 0.72 = 3.52 \quad (39)$$

The signal power required to reach half the saturation gain is

$$S_h/a = 1.00 \text{ W/cm}^2 \quad (40)$$

and for a 40  $\mu\text{m}$  diameter fiber

$$S_h = 12.6 \text{ } \mu\text{W} \quad (41)$$

Thus, the results for the gain  $G$  as a function of the initial signal power  $S_0$

$$G = 3.52 \left( \frac{1}{1 + 12.6/S_0} \right) \quad (42)$$

Comparing this result with Equation 34 for lithium, we conclude that although sodium has only 30% of the saturation gain of lithium, it approaches the saturation limit much faster. The two  $G(S_0)$  curves of Equation 34 and 42 intersect at  $G = 2.4$  with  $S_0 = 28 \text{ } \mu\text{W}$ , below which sodium has the larger gain. Thus, the advantage of a lithium transistor comes into play only if larger signal powers are available.

## 5. CONCLUSIONS AND PLANS

The preceding analysis has addressed suitable examples of free-atom media for optical switch and transistor operations. Both of these operations are predicted as possible with the relatively high speed of response (or bandwidth) and low demands on control and signal power which had been expected for free-atom media and, in particular, for the selected examples of lithium and sodium. In transistor operation, photon amplification factors of up to 11, and total gains of up to 12, are found. The next priority of investigation concerns the class of quasi-free atom media, especially rare earth ions or atoms interstitially or substitutionally added to the solid fiber material. Although time constants of response and requirements for power and amounts of material are generally expected to be larger, an overriding advantage may be found in transistor gain. Also to be considered are the dense matter media, including such liquid dyes as have proven useful in tunable lasers.

The reason for this broad treatment of eligible media is the possibility of combining a narrow-line transistor with a suitable broadband transistor to form a gain unit which can be used in cascade for ac photon multiplication. Lithium and sodium are eligible narrow-line transistor materials.

It should be added that experiments could now be performed to demonstrate with lithium or sodium the first optical transistor operation and also a high-speed optical switch (uranyl has already been demonstrated as a switch of about  $10^3$  times lower speed). The incorporation of sodium or lithium (if in fact chosen for this purpose) into a device for integrated optics will, of course, require further work. However, the fact that only  $10^{12}/\text{cm}^2$  Li or Na atoms are required

facilitates the attainment of this objective. Suitable methods will be discussed in a later report, if indeed these metals turn out to be the materials of choice for narrow-line optical transistors or switches.

## 6. REFERENCES

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5. C. C. Corliss and W. R. Bozman, "Experimental Transition Probabilities for Spectral Lines of Seventy Elements," NBS Monograph 53 (1962).
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## APPENDIX I

In this section we use steady-state rate equations to derive Equation 22, used to calculate the gain in the optical transistor.

An amount of control power,  $P_{abs}$ , absorbed in the device corresponds to  $\frac{P_{abs}}{h\nu_{12}}$  photons absorbed. Similarly, the signal power  $S_0$  corresponds to  $\frac{S_0}{h\nu_{23}}$  photons.

Under steady-state conditions the population densities  $N_2$  and  $N_3$  in levels 2 and 3 are constant. For level 2 we can, therefore, write

$$0 \equiv L \frac{dN_2}{dt} = \frac{P_{abs}}{ah\nu_{12}} - \gamma_{12} \cdot N_2 \cdot L + \gamma_{23}N_3 \cdot L - \sigma_{32} \cdot \frac{S_0}{ah\nu_{23}} \cdot (N_2 - \frac{g_2}{g_3} N_3)L \quad (A-1)$$

Here  $\frac{P_{abs}}{h\nu_{12}}$  is, as described above, the number of photons absorbed from the control beam;  $\gamma_{12}N_2L$  is the spontaneous decay of population  $N_2$  with the time constant  $\frac{1}{\gamma_{12}}$ ;  $\gamma_{23}N_3 \cdot L$  is the radiative relaxation of population  $N_3$ ; and  $\gamma_{32} \frac{S_0}{ah\nu_{23}} (N_2 - \frac{g_2}{g_3} N_3)L$  is the balance of absorption and stimulated transitions between levels 2 and 3 caused by the signal beam  $S_0$ .

In the same way we find for level 3

$$0 \equiv L \frac{dN_3}{dt} = \sigma_{32} \cdot \frac{S_0}{ah\nu_{23}} \cdot (N_2 - \frac{g_2}{g_3} N_3) L - \gamma_{23}N_3 \cdot L \quad (A-2)$$



Equations A-1 and A-2 give

$$\frac{P_{abs}}{ahv_{12}} = L \cdot \gamma_{12} \cdot N_2 \quad (A-3)$$

From Equations A-1, A-2, and A-3 we find the signal power  $S$  leaving the transistor after undergoing absorption caused by the control power  $P_{abs}$

$$S = S_o - hv_{23} \cdot \frac{P_{abs}}{ahv_{12}} \cdot \frac{\frac{1}{\gamma_{12}}}{\frac{g_2}{g_3} \cdot \frac{1}{\gamma_{23}}} \cdot \frac{1}{1 + \frac{1}{\frac{g_2}{g_3} \cdot \frac{1}{\gamma_{23}} \cdot \sigma_{32} \cdot \frac{S_o}{ahv_{23}}}} \quad (A-4)$$

This calculation is valid for

$$S_o \gg S_o - S,$$

i.e., for a small depletion of the signal beam. Similar results are obtained for higher depletions but the calculations are more complicated.

We define the amplification,  $G$ , in the optical transistor as the ratio between the change,  $\Delta S$ , in the signal power  $S$  leaving the device to the corresponding change in the absorbed control power,  $\Delta P_{abs}$ . From Equation A-4 we have

$$G = \frac{\Delta S}{\Delta P_{abs}} = \frac{dS}{dP_{abs}} = G_f \times G_{ph} = \frac{v_{23}}{v_{12}} \times \frac{\gamma_{23} g_3}{\gamma_{12} g_2} \cdot \frac{1}{1 + \frac{1}{\frac{S_o}{\gamma_{23} ahv_{23}} \cdot \frac{g_2}{g_3} \cdot \frac{1}{\gamma_{23}}}}$$

which is identical to Equation 22.

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